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MEASURING SOIL TRAFFICABILITY
CHARACTERISTICS

S. J. Knight, et al

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

December 1961

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U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS

Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

Preface

This paper was prepared for presentation at the 1961 Winter Meeting of the American Society of Agricultural Engineers, Chicago, Illinois, 12-15 December 1961. It has been designated ASAE Paper No. 61-609. It is based on work being conducted by the Waterways Experiment Station for the Office, Chief of Engineers, and was reviewed and approved for presentation by that office.

MEASURING SOIL TRAFFICABILITY CHARACTERISTICS

Summary

The Army's need to predict the performance of military vehicles in a wide range of soil and snow conditions has been met by the results of an empirical test program. Soil and snow conditions were quantitatively indicated in terms of the resistance offered by the soil and snow to being probed with a simple instrument, called the cone penetrometer, and vehicles were tried out on various soil and snow conditions. On the basis of statistical evidence, vehicle performance and cone index have been correlated. The results of the Army study may possibly be applied to the solution of agricultural problems involving the interrelations of tractors and soils.

MEASURING SOIL TRAFFICABILITY CHARACTERISTICS

by

S. J. Knight* and D. R. Freitag**

Introduction

Agricultural engineers are becoming increasingly aware of the need for fundamental knowledge of the interrelations between farm machinery and soils to apply to the solution of the ever-growing problems in soil compaction, deep tillage, and generally more efficient and economical land management. Research to acquire such knowledge, long almost the sole concern of the U. S. Department of Agriculture and a few universities, is now being performed by many major manufacturers of farm equipment in this country and abroad, and the list of research-conscious companies and universities is growing rapidly.

The Army also has a need for knowledge of soil-vehicle relations--in its quest for a high degree of mobility. The present military doctrine of mobility calls for small and widely dispersed units which can assemble quickly into a large force, deliver an attack, and immediately redisperse to minimize the possibility or effects of a nuclear retaliation. This means the Army can no longer move along highways and railroads, but must strike out across the natural terrain.

Two important goals are implied in the new military doctrine. First, vehicles are needed that can travel over rougher and softer terrain faster than ever before, and second, commanders must know whether the particular vehicles they control can or cannot negotiate the areas which lie ahead. Both these goals are being pursued in research at the Army Mobility Research Center (AMRC) of the U. S. Army Engineer Waterways Experiment Station (WES) at Vicksburg, Mississippi.

The studies aimed at the development of more mobile vehicles, called mobility studies, are fundamental investigations of the stresses induced by the vehicles, the strains undergone by the soils, and their interrelations. They are studies that require carefully controlled laboratory experiments and precise measurements. They are long-term studies, and

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their results, even the interim results, are directly applicable to many of the problems facing the agricultural engineer today. For this reason the National Tillage Machinery Laboratory at Auburn, Alabama, and the Army Mobility Research Center work closely in their vehicle mobility research programs.

The studies aimed at providing military commanders with the knowledge of their vehicle capabilities in any terrain, called trafficability studies, have necessarily been empirical because their results were needed in a minimum of time and in simple terms suitable for military employment. These studies are now well advanced, and the results therefrom are being incorporated into standard military practices of deployment. It is considered that some of these results also may be useful in the agricultural engineering field. It is the purpose of this paper, therefore, to describe the instruments and techniques developed at the AMRC for the measurement of soil trafficability characteristics with the thought that they might be employed, perhaps with modifications, to assist in selection of suitable farm machinery from the standpoint of reducing compaction effects and estimating drawbar pull for a range of soil conditions. In addition, the paper has another purpose: to emphasize the necessity for quantitative measurements of soil conditions for use in the many comparison trials that inevitably must be performed by manufacturers in determining the superiority of one tire over another or of one tractor over another. The word "inevitable" is used because it must be recognized that the day when such comparisons can be made fully and with complete confidence on the drawing board is not yet at hand, and, in fact, may never arrive. (Despite advanced knowledge in the automotive and aerodynamic fields, occasional "lemons" in automobiles and aircraft still make their appearance.) The phrase, "quantitative measurements," is used because too often qualitative terms, such as "muddy" or "sandy" or "tilled," are employed for describing soil conditions in comparative trials. Not only are such descriptions almost meaningless when attempts are made to compare the results of trials in two nonadjacent areas, but they may not even be truly meaningful when the trials are made concurrently in the same area because homogeneity of soil condition is the rare exception, not the rule.

Basic Trafficability Considerations

The Army's trafficability studies have, for the most part, been concerned with very soft soils--soils which, in fact, were "too wet to plow," at least by former standards. As a result, the data to be presented may be less applicable to current farming practices than to doctrine which advocates earlier spring plowing, popular in European countries, and growing popular in this one.

To be adequate for a vehicle, a soil must have sufficient bearing capacity to prevent the vehicle from sinking too deeply and sufficient traction capacity to provide the necessary forward thrust of the vehicle's wheels or tracks. Both bearing capacity and traction capacity are

functions of the shear strength of a soil. Usually a vehicle is immobilized by a concurrent failure in bearing and traction, and it is not possible to separate the two effects. Traction failure can occur on a soil with adequate bearing strength, as when a rubber-tired vehicle merely spins its wheels but does not sink appreciably, but sinkage failure does not occur without being accompanied by traction failure.

Instruments

In the trafficability studies, bearing-traction capacity was measured empirically in terms of the cone index, which is the pounds of force that must be applied to the handle of the cone penetrometer (shown in figure 1) per square inch of end area of its cone tip in order to force it into the ground. The right circular, 30-degree cone, not visible in the photo, has an end area of $1/2$ sq in. The cone is pushed slowly downward, and readings of the dial gage are made at desired vertical increments which are shown by graduations on the instrument's shaft. It is pointed out that the cone penetrometer's value as a tool for measuring bearing-traction capacity lies solely in the fact that it has been used in many, many tests to correlate vehicle performance with soil condition, and not in some planned or fortuitous feature of shape or size. It is postulated that any instrument that is capable of probing the soil to various depths and shearing it in a consistent manner would have been equally successful. As a matter of fact, in an early program of trafficability tests on sands, four different instruments (including the cone penetrometer) were used and the quality of correlation between instrument reading and vehicle performance hardly differed for the four. Photographs of the three other instruments used are shown in figure 2.

Many fine-grained* soils (clay, silty clay, clay loam, loam, etc.) whose strengths are low in situ will become even weaker under the action, or remolding effect, of a vehicle. In order to estimate the cone index that will obtain under the moving vehicle, a remolding test was devised. This test consists of measurement of the cone index of a sample of soil confined in a small cylinder before and after pounding it with 100 blows of a 2-1/2-lb tamper falling 12 in. A "remolding index" is obtained by dividing the cone index of the soil after it has been pounded by its cone index before the blows were applied. Figure 3 illustrates the various stages of this test. A "rating cone index," the final measure of a soil's trafficability, is obtained by multiplying the in situ cone index by the remolding index.

* A fine-grained soil is one in which more than 50% by weight of its grains are smaller than 0.074 mm in size (Unified Soil Classification System).

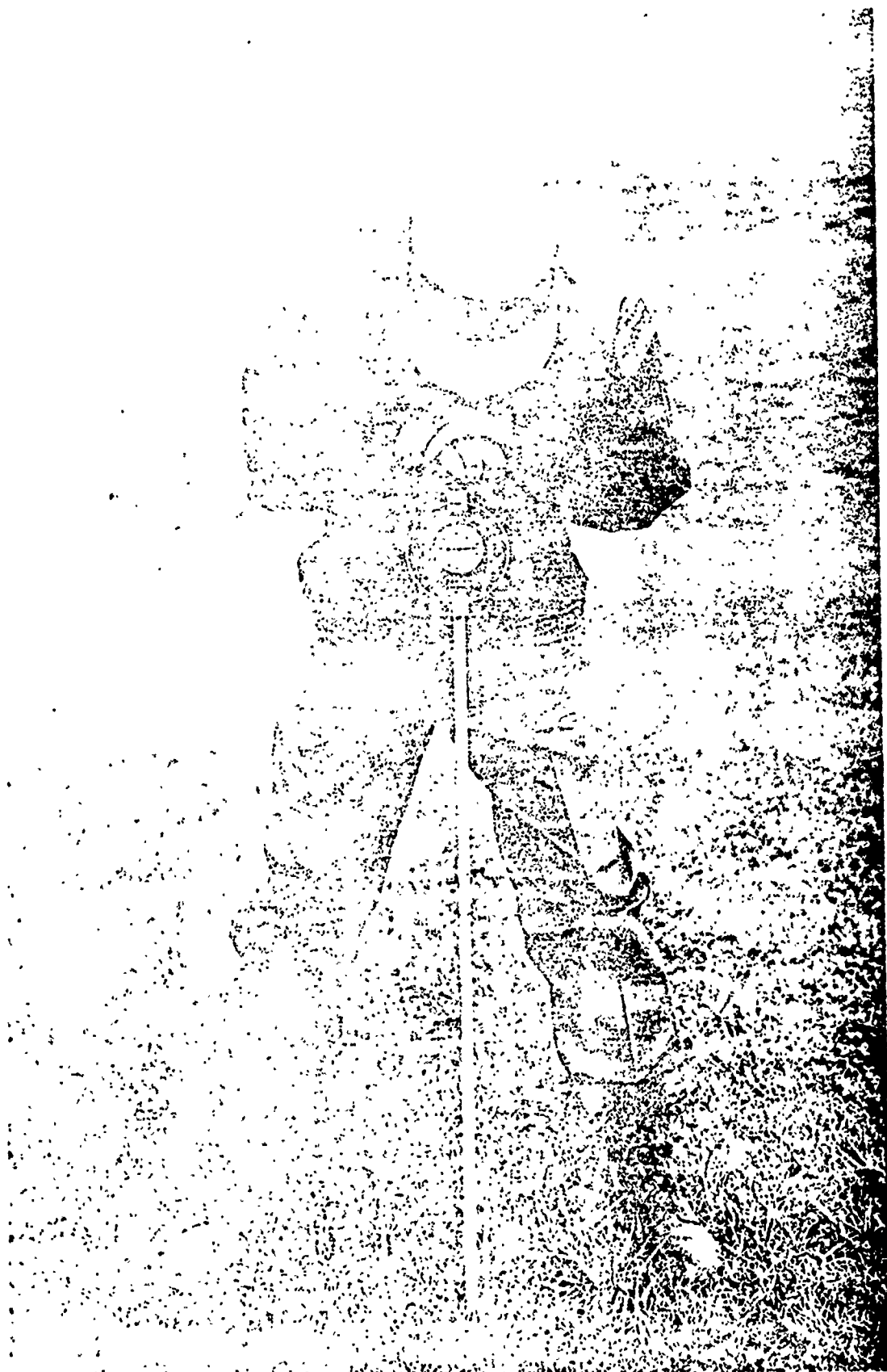
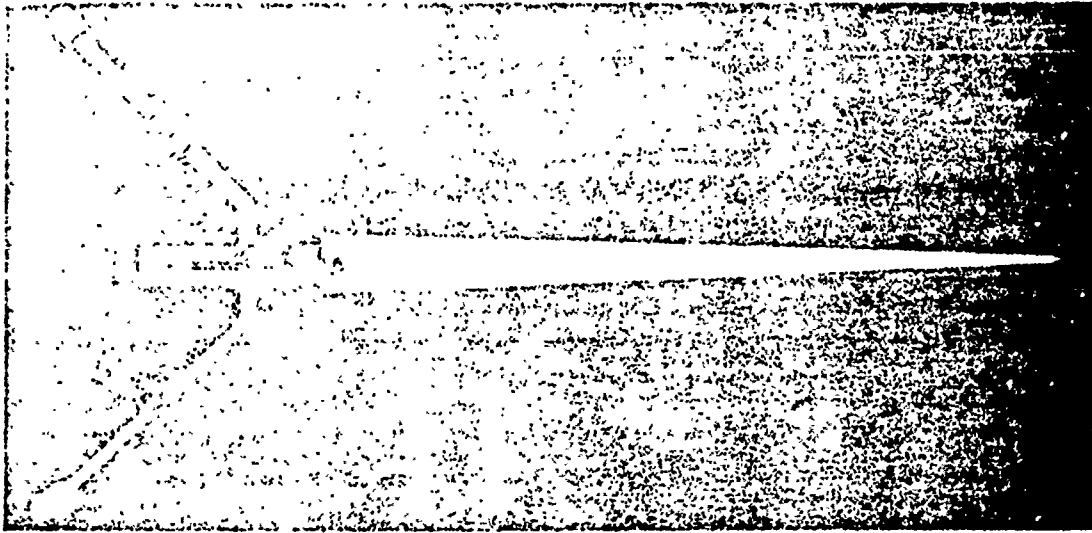
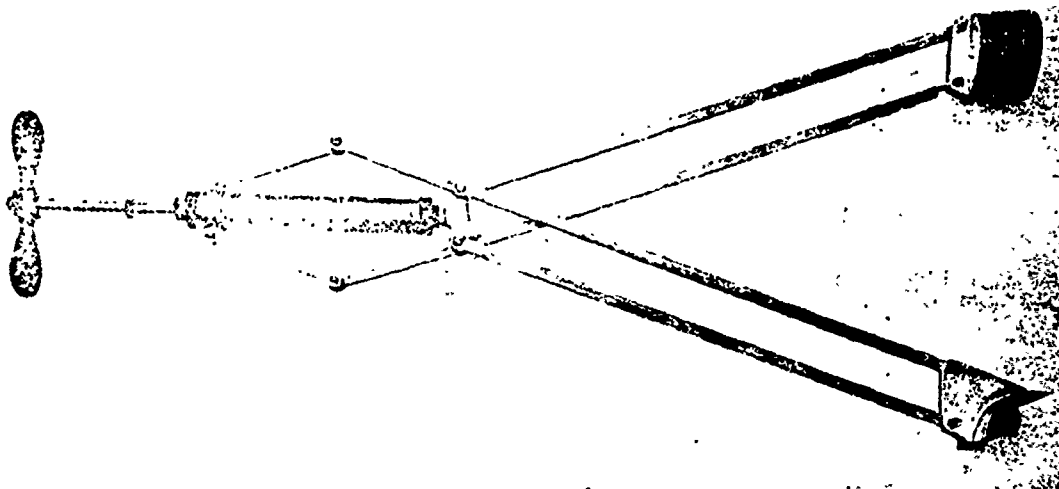


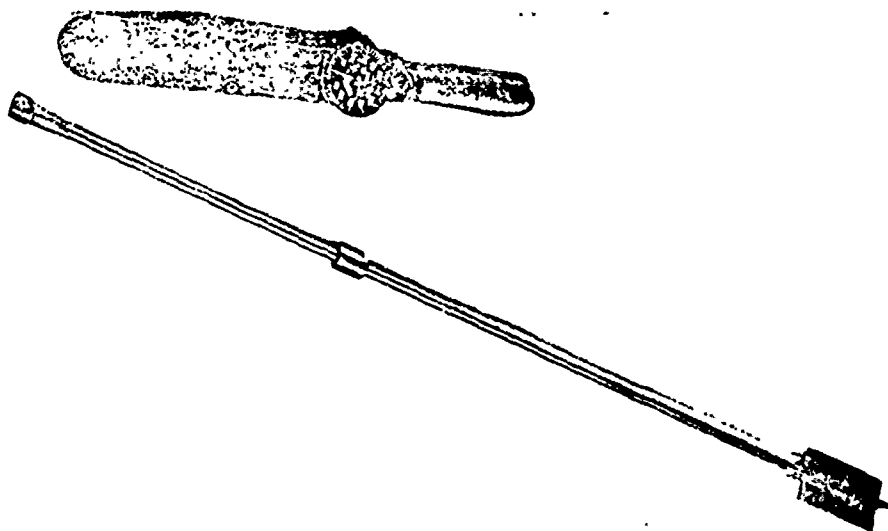
Figure 1. Measuring cone index with cone penetrometer



Taper penetrometer

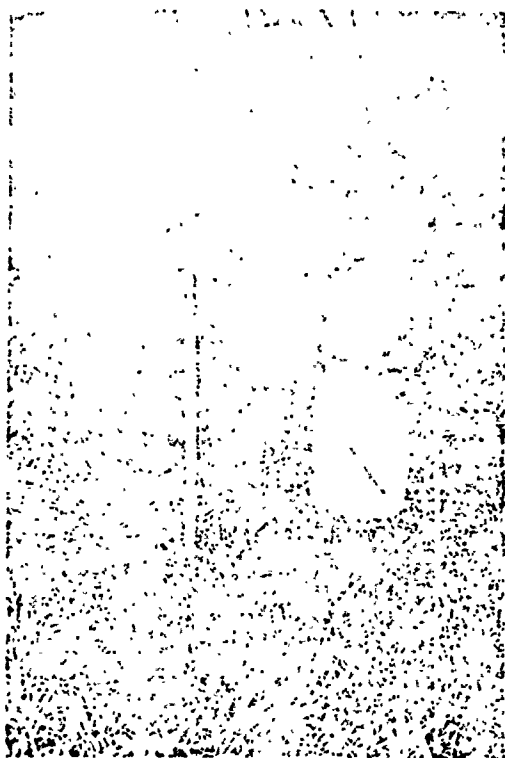


Truss



Shear vane

Figure 2



Taking sample



Loading cylinder



Measuring cone index before
blows are applied



Applying blows

Figure 3. Remolding test equipment and procedures

Vehicle Performance-Cone Index Correlations
in Fine-Grained Soils

From data collected in hundreds of tests with several types of military vehicles on many types of fine-grained soils in widely scattered locations, it has become feasible to predict the performance of these vehicles on the basis of the rating cone index. If the rating cone index of a given area is known, one can predict confidently whether a given vehicle will be able to cross it once, whether 50 vehicles can cross in the same path, how heavy a load the vehicle can tow through it, or how steep a slope the vehicle can climb. For most vehicles the correlations are of the highest quality when the rating cone index of the soil in the layer from 6 to 12 in. below the surface is considered. For very light vehicles the critical layer is 3 in. closer to the surface, and for very heavy vehicles the critical layer is 3 in. deeper.

The following table shows the minimum rating cone index necessary for completion of one pass and 50 passes (called vehicle cone index) for four military vehicles, a construction tractor, and an agricultural tractor. The vehicle cone index for the agricultural tractor was computed as explained on page 9.

| <u>Vehicle</u> | <u>Description</u> | <u>Rating Cone Index for 1 Pass</u> | <u>Rating Cone Index for 50 Passes (Vehicle Cone Index)</u> |
|-----------------------------|---------------------------------------------|---------------------------------------------|-----------------------------------------------------------------------------|
| M29C weasel | 5,500-lb, tracked, amphibious cargo carrier | 20 | 25 |
| M48 tank | 90,000-lb medium tank | 40 | 50 |
| M37 3/4-ton weapons carrier | 7,400-lb (with load of 1,500 lb) 4x4 truck | 50 | 65 |
| M135 2-1/2-ton cargo truck | 16,300-lb (with load of 5,000 lb) 6x6 truck | 45 | 60 |
| D7 engineer tractor | 35,000-lb crawler-type construction tractor | 30 | 40 |
| Farmall 560 tractor | 7,170-lb with tricycle configuration | 36 | 48 |

Cone indexes required for 50 passes of a vehicle up a given slope or for 50 passes towing a given load on level terrain can be determined by using the curves shown in figure 4a. Note that "vehicle cone index" is the zero point of the abscissa. The force required to tow a piece of wheeled or tracked machinery over a range of soil conditions can be estimated using

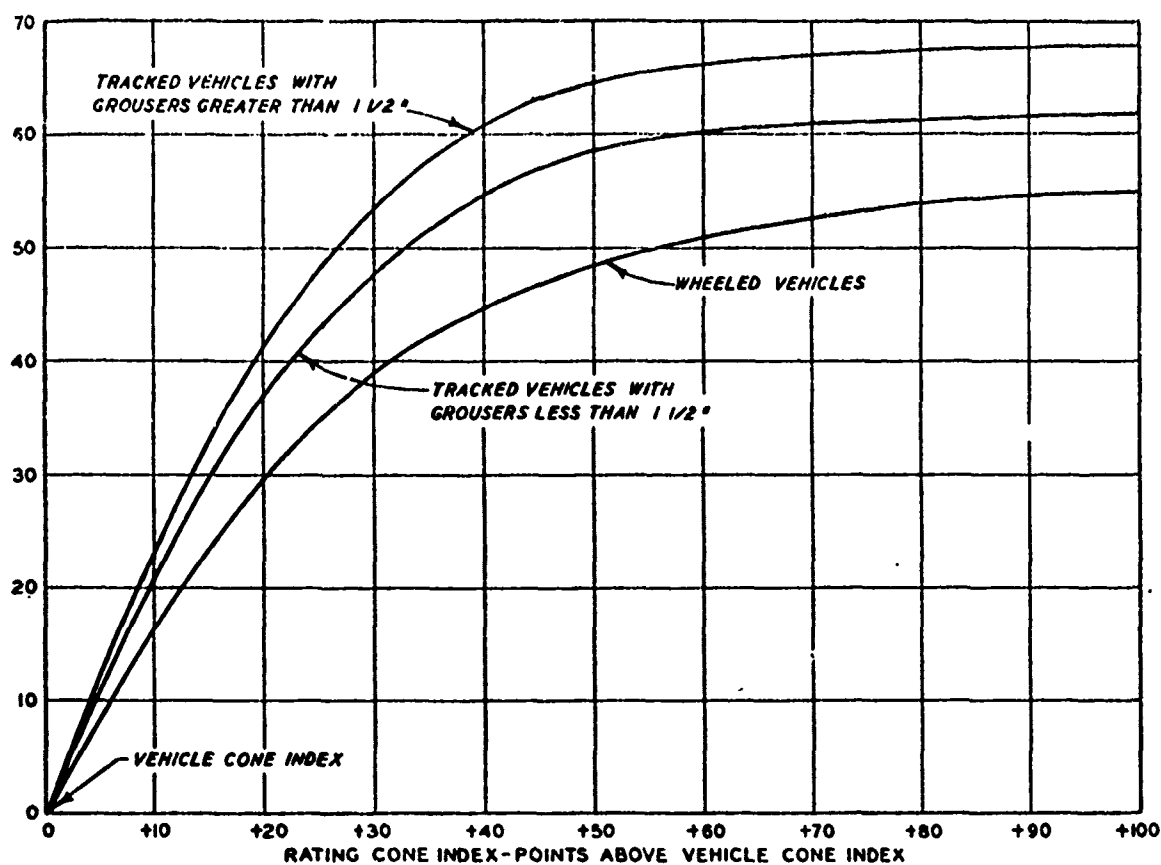


Figure 4a. Maximum towing force (on level ground) and maximum slope negotiable vs rating cone index expressed as points above vehicle cone index

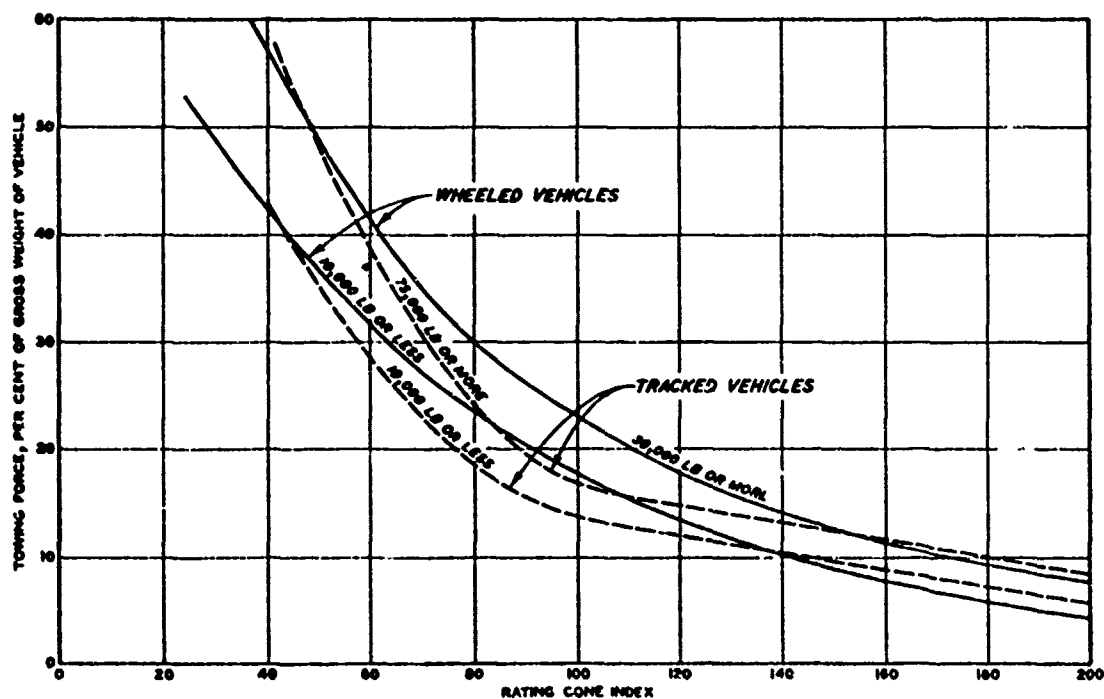


Figure 4b. Towing force required for wheeled and tracked vehicles on level ground

the curves in figure 4b. The curves apply only to free-rolling, idle equipment, not to equipment engaged in tilling or other activities that would add to the rolling resistance. The curves shown in figures 4a and 4b are average curves drawn from the results of tests with many different vehicles. In general, however, curves for individual vehicles have been found to deviate very little from the average. Using the data collected in actual vehicle tests, a system was developed for evaluating the effects of a vehicle's characteristics (weight, contact pressure, etc.) in terms of mobility index and thence in terms of vehicle cone index. The system comprises four formulas--one formula for self-propelled tracked vehicles, another for self-propelled wheeled vehicles, and one each for towed tracked and wheeled vehicles. These formulas are shown in Appendix A. The formulas for self-propelled tracked and wheeled vehicles have been verified by many tests with vehicles not used in its development, and have been found to be entirely satisfactory. There has been little opportunity as yet to check the less important formulas for towed vehicles.

amplifier!

The vehicle cone index of the agricultural tractor was computed by assuming the rear half to be a self-propelled two-wheeled vehicle and the front half to be a two-wheeled towed vehicle. The vehicle cone index for the rear half was computed at 40, and a maximum towing force versus rating cone index curve was drawn. This was accomplished by merely changing the scale on the abscissa of figure 4a from 0, +10, etc., to 40, 50, etc. Then the towing force versus rating cone index curve for the front half of the tractor was transposed from figure 4b to figure 4a in terms of the weight of the rear half of the vehicle. The intersection of the two curves, 48, was considered to be the vehicle cone index for the tractor. The minimum rating cone index required for one pass of the agricultural tractor is 75% of the vehicle cone index, or 36. Technique of analysis used here has been successfully applied to tractor-trailer combinations to determine their vehicle cone indexes. However, since the Army has performed no tests with vehicles with widely differing front and rear wheels and widely unbalanced weight distribution, a few tests should be made to verify the applicability of this technique to the computation of vehicle cone indexes for agricultural tractors with these characteristics.

Vehicle Performance-Cone Index Correlations in Sand

Sand, as used here, is defined as a soil in which less than 7% (by weight) of its constituent material is finer than 0.074 mm in size, and not more than 10% is coarser than 4.76 mm. Sand is found on beaches, deserts, or bars in large rivers. It is not of much interest from an agricultural standpoint, and will therefore be only briefly treated in this paper.

Most of the trafficability research in sand has been concerned with wheeled vehicles since tracked vehicles are seldom immobilized in level sand. In fact, even wheeled vehicles, if equipped with proper tires at proper inflation pressures, are seldom immobilized on level sands, unless

the sands are in a quick or near-quick condition. This fact was somewhat of a hindrance in the research since it was not feasible to determine a dry, level sand condition soft enough to immobilize a vehicle, and thus clear-cut differentiation between "go" sands and "no go" sands could not be made. Instead, a correlation between maximum slope a vehicle could climb and the strength of the sand was sought.

Tire pressure significantly affects the ability of a wheeled vehicle to climb a sand slope. (Tire pressure appeared to be practically insignificant in the operation of vehicles on soft, fine-grained soils, especially where repetitive traffic was concerned.) Therefore, the correlations developed include the inflation pressure in the vehicle's tires.

The same cone penetrometer used for fine-grained soils was also used to measure the strength of sand. The main difference was that instead of the cone index of a subsurface layer, the cone index of the top 6 in. appeared to represent the sand condition best. Also, although the strength of sand is known to change under a moving vehicle, it was not necessary to recognize this in establishing good correlations.

The tests consisted of measuring the angle (actually the tangent of the angle) of a slope, the cone index of the sand on the slope, and then trying out the vehicle on the slope. The "correlation" consisted of plotting successful performance of the vehicle by one symbol, immobilization by another, and drawing a curve separating the two symbol types. Figure 5a is an example of such an analysis, and also is a timely device for conveying to the reader an appreciation of the degree of accuracy typical of the trafficability studies in general. Notice that the line does not cleanly divide immobilizations from nonimmobilizations, i.e. three points on the left side of the line should be on the right, and two on the right should be on the left. The curve is a very good tool for estimating the slope-climbing ability of the truck (at 10-psi inflation pressure) when the cone index of the sand is known, but it should not be considered an infallible one. Although difficult to demonstrate statistically, it is the consensus of engineers who have been engaged in trafficability research for a number of years that the accuracy of predicting vehicle performance in terms of go-no go, slope-climbing ability, and maximum drawbar pull is in the order of 90 to 95% when the soil condition is measured in terms of cone index. Figure 5b shows a family of curves for varying tire pressures for the same vehicle.

The type of testing described has been performed with the most commonly used military vehicles on many kinds of sands (quartz, coral, volcanic) on beaches and deserts. The vehicles used range from a jeep through a 5-ton truck. The data obtained are being used to develop a formula for the mobility index of wheeled vehicles in sand. One formula now being tested considers such factors as the tire-inflation pressure in pounds per square inch, ply rating, slope in per cent, number of driving wheels, tire width in inches, and outside wheel diameter in inches. The final formula will be similar in form and function to those for vehicles operating in fine-grained soils (Appendix A).

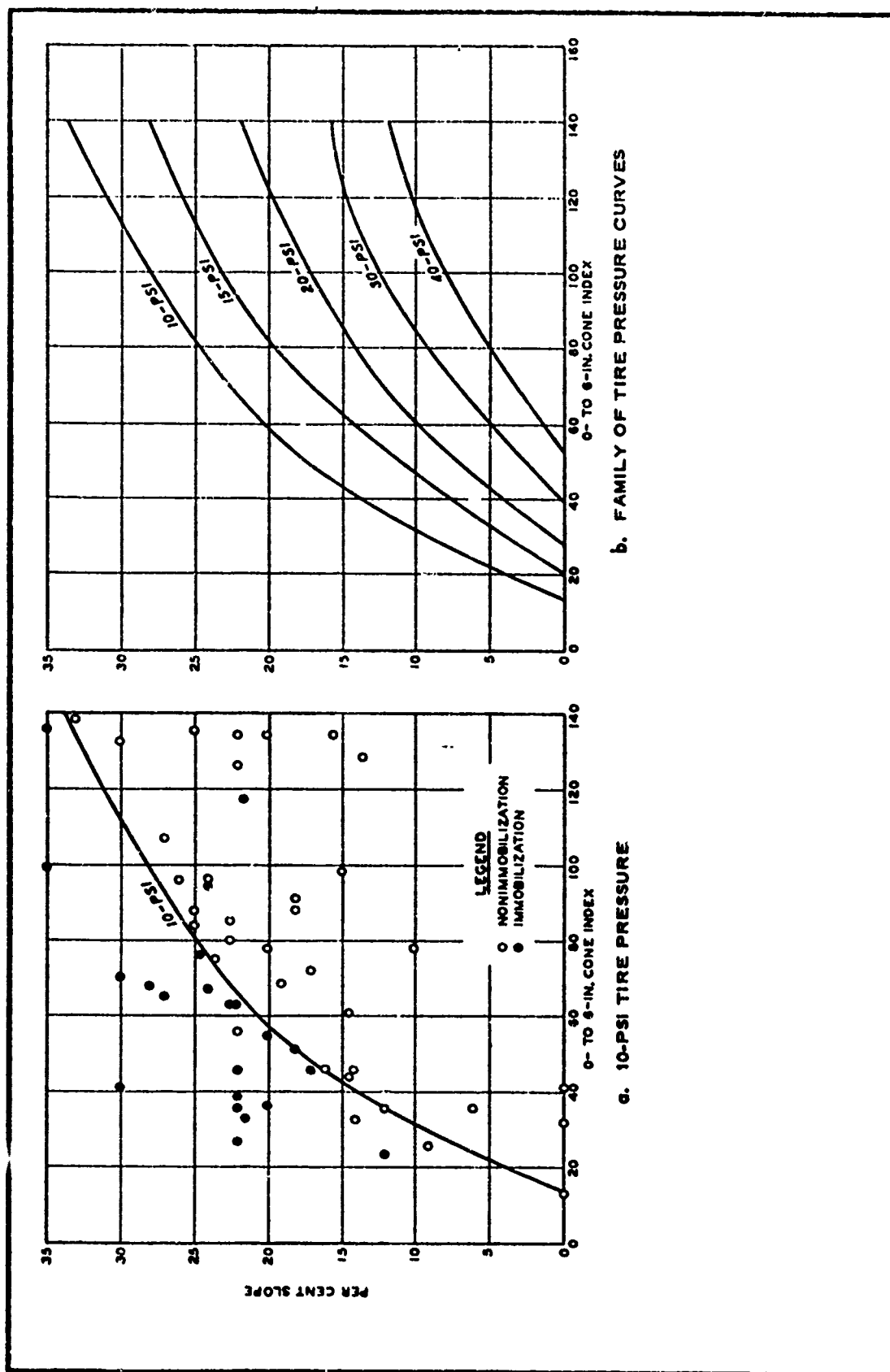


Figure 5. Slope vs cone index; 2-1/2-ton 6x6 truck equipped with 11.00-20, 12-PR tires (single), dry-to-moist sand

Vehicle Performance-Cone Index Correlations in Snow

In recent years the Corps of Engineers' trafficability studies have been extended to include problems of travel in snow-covered regions. Vehicle tests have been conducted in both shallow and relatively deep, soft snows of the continental United States and Canada and in the very deep snows of the Greenland icecap. Since snow is of no direct agricultural importance, no details will be given of this program. It suffices to say that the same instruments and general techniques that have been proved in the soil test programs also appear to be applicable to the work in snow.

Summary

The results of the Army's research in the measurement of soil trafficability characteristics could be applied to the solution of certain agricultural engineering problems dealing with tractors. For example, the mobility index formulas and curves shown, perhaps modified after the accumulation of suitable experimental data, could be used to evaluate the compaction effects of tractors and towed implements, since presumably the tractor or implement with the lowest vehicle cone index will produce the least harmful compaction, and to estimate the towing and slope-climbing ability of a tractor on soft soils.

The consistent use of the cone penetrometer for measurement of soil conditions has made it feasible for the Army to compare vehicle performance on many types of fine-grained soil and (separately) many kinds of sand and snow in widely scattered locations. Consistent use of the cone penetrometer, perhaps equipped with a smaller size cone to permit measurements in soils firmer than those studied by the Army, or an equivalent instrument in agricultural engineering research should result in similar accomplishments.

APPENDIX A: MOBILITY INDEX (For Fine-Grained Soils)

The mobility index is a dimensionless number obtained by applying certain characteristics of a vehicle to the formulas given subsequently. The mobility index can then be applied to the curve shown in fig. A1 to determine the vehicle cone index.

Self-propelled tracked vehicles

$$\text{Mobility index} = \left(\frac{\text{contact pressure}}{\text{track factor}} \times \frac{\text{weight factor}}{\text{grouser factor}} + \frac{\text{bogie factor}}{\text{clearance factor}} \right) \times \text{engine factor} \times \text{transmission factor}$$

wherein,

$$\text{contact pressure} = \frac{\text{gross weight in lb}}{\text{area of tracks in contact with ground in sq in.}}$$

weight factor: less than 50,000 lb = 1.0
 50,000 to 69,999 lb = 1.2
 70,000 to 99,999 lb = 1.4
 100,000 lb or greater = 1.8

$$\text{track factor} = \frac{\text{track width in in.}}{100.}$$

grouser factor: grousers less than 1.5 in. high = 1.0
 grousers more than 1.5 in. high = 1.1

$$\text{bogie factor} = \frac{\text{gross weight in lb divided by 10}}{(\text{total number of bogies on tracks in contact with ground}) \times (\text{area of 1 track shoe in sq in.})}$$

$$\text{clearance factor} = \frac{\text{clearance in in.}}{10}$$

engine factor: 10 or greater hp per ton of vehicle wt = 1.0
 less than 10 hp per ton of vehicle wt = 1.05

transmission factor: hydraulic = 1.0; mechanical = 1.05

Self-propelled wheeled vehicles

$$\text{Mobility index} = 0.5 \left[\left(\frac{\text{contact pressure}}{\text{tire factor}} \times \frac{\text{weight factor}}{\text{grc'er factor}} + \frac{\text{wheel load}}{\text{clearance factor}} \right) \times \text{engine factor} \times \text{transmission factor} \right] + 20$$

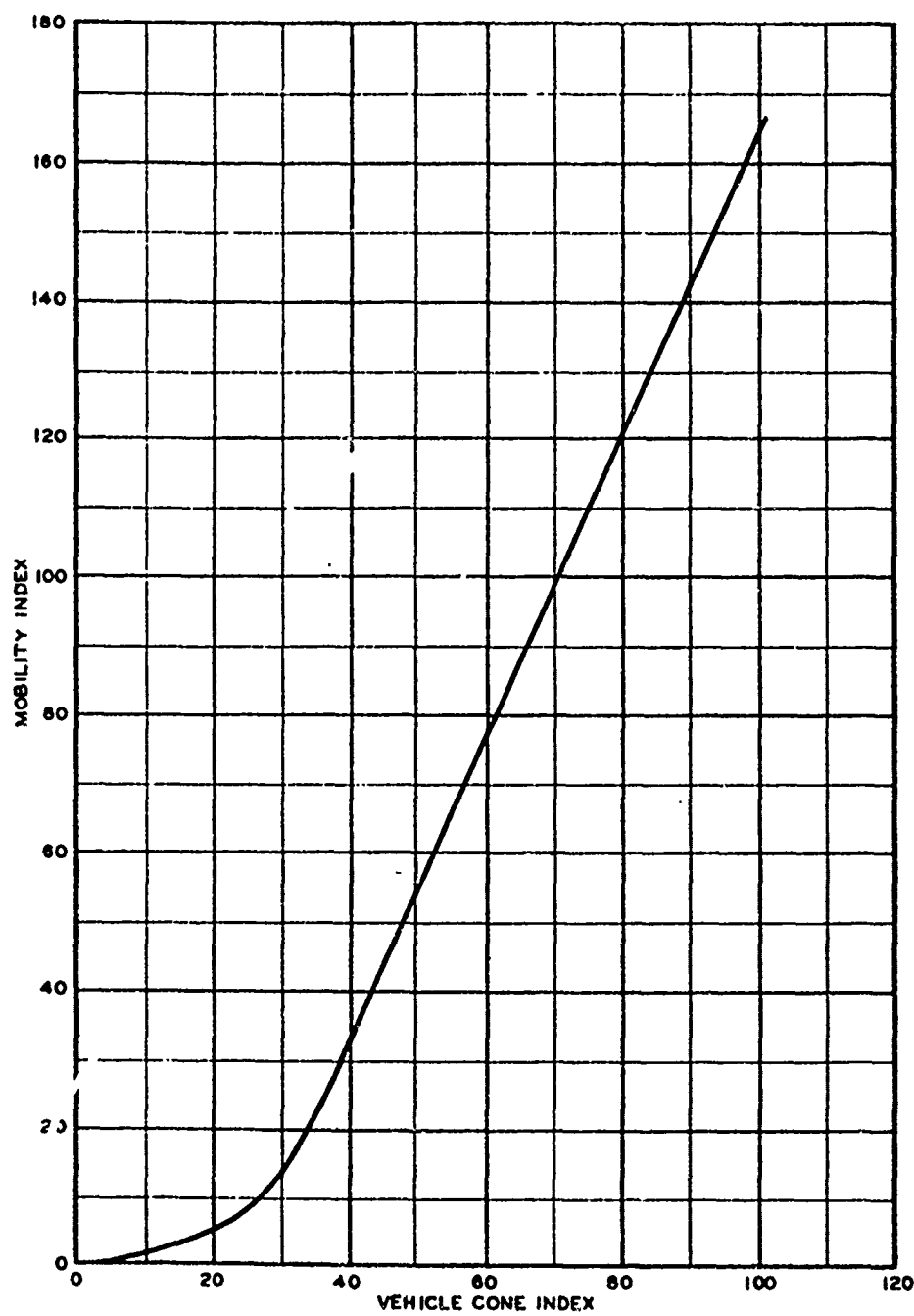


Figure A1. Mobility index vs vehicle cone index

wherein,

$$\text{contact pressure factor} = \frac{\text{gross weight in lb}}{\text{tire width} \times \text{rim diam} \times \text{No. of tires}}$$

weight factor: greater than 35,000 lb = 1.1
 15,000 to 35,000 lb = 1.0
 less than 15,000 lb = 0.9

$$\text{tire factor} = 1.25 \times \text{tire width in in. divided by 100}$$

grouser factor: with chains = 1.05
 without chains = 1.00

$$\text{wheel load} = \frac{\text{gross weight in kips}}{\text{No. of wheels}} \quad (\text{wheels may be single or dual})$$

$$\text{clearance factor} = \frac{\text{clearance in in.}}{10}$$

engine factor: greater than 10 hp per ton = 1.0
 less than 10 hp per ton = 1.05

transmission factor: hydraulic = 1.0; mechanical = 1.05

Towed tracked vehicles

$$\text{Mobility index} = \left(\frac{\text{contact pressure} \times \text{weight factor}}{\text{track factor}} + \text{bogie factor} - \text{clearance} \right) + 30$$

wherein,

$$\text{contact pressure} = \frac{\text{gross weight in lb}}{\text{area of tracks in contact with ground in sq in.}}$$

weight factor: 15,000 lb or greater = 1.0
 below 15,000 lb = 0.3

$$\text{track factor} = \frac{\text{track width in in.}}{100}$$

$$\text{bogie factor} = \frac{\text{gross weight in lb divided by 10}}{(\text{total No. of bogies on track in contact with ground}) \times (\text{area of 1 track shoe in sq in.})}$$

clearance = clearance in in.

Towed wheeled vehicles

$$\text{Mobility index} = 0.64 \left(\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{tire factor}} + \text{axle load} - \text{clearance} \right) + 10$$

wherein,

contact pressure factor = $\frac{\text{normal tire pressure in lb per sq in.}}{2}$

weight factor: 15,000 lb per axle or greater = 1.0
 12,500 to 14,999 lb = 0.9
 10,000 to 12,499 lb = 0.8
 7,500 to 9,999 lb = 0.7
 less than 7,500 lb = 0.6

tire factor: single tire = $\frac{\text{width in in.}}{100}$

dual tire = $\frac{1.5 \times \text{width in in.}}{100}$

axle load = $\frac{\text{axle load in lb}}{1000}$

clearance = clearance in in.